Technical Report 2009-DRAFT

IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

EFFECTS OF LOWERED NIGHTTIME VELOCITIES ON FISHWAY ENTRANCE SUCCESS BY PACIFIC LAMPREY AT BONNEVILE DAM AND FISHWAY USE SUMMARIES FOR LAMPREY AT BONNEVILLE AND THE DALLES DAMS, 2008

Report for Project
ADS-P-00-8

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U.S. Army Corps of Engineers
Portland District

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Executive Summary

Adult Pacific lamprey *Lampetra tridentata* encounter various obstacles to upstream migration at Columbia and Snake River hydropower dams. Previous radiotelemetry studies indicate that lamprey have particular difficulty entering fishway entrances and passing through transition areas, past count windows, and in serpentine weir sections of the fish ladders. The primary objectives of the 2008 radiotelemetry study were to:

1) Evaluate the effects of lowered water velocities (zero head differential) at fishway entrances at Bonneville Dam on lamprey behavior and passage efficiency.

2) Evaluate lamprey passage efficiencies, passage times, fishway entrance use patterns, and fallback at the Bonneville, The Dalles, and John Day dams.

3) Evaluate lamprey behaviors near the Bonneville Dam count windows and serpentine weirs.

Of 595 lamprey tagged and released, 443 (74%) approached the dam, 318 (53%) entered, and 156 (26%) passed the dam. Fifty-six percent of the tagged lamprey made their first approach at Powerhouse 2 (PH2), followed by Powerhouse 1 (PH1) (30%) and the spillway (14%). The percentage of fish that entered the same fishway as they first approached ranged from 52.7% at PH2 north to 91.7% at PH1 north.

Entrance efficiencies were calculated for 1) nonexperimental times (includes all hours) and 2) experimental times (nighttime approaches and entries only). Nonexperimental entrance efficiencies of the tagged lamprey (the total number of unique fish that approached / total number of same fish that successfully entered for all hours) ranged from 51% at spillway entrances to 68% at PH1 entrances.

At the PH2 north entrances, entrance efficiencies for fish making their first fishway approach (total # first entries / total # first approaches at same entrance) was 4% (2 entered out of 45 that approached) when fish units were placed on standby versus < 1% (1 entry out of 107 approaches) during normal velocity. At the PH2 south entrances, efficiencies for fish making their first approach was 14% (3 entries out of 21 approaches) during standby operation and 18% (10 entries out of 55 approaches) during normal velocities.

Taking into account all approaches and entries, entrance efficiencies (total # of entries / total # approaches at same entrance between 2200 and 0400) was 9% (PH2 north) and 30% (PH2 south) at normal velocity and 2% (PH2 north) and 12% (PH2 south) during standby operation. Standby conditions at entrances had an overall negative effect on lamprey passage. Once fish entered the fishway during the standby operation they were more likely to exit the fishway

Overall dam passage efficiency (the number of tagged lamprey that passed over the dam divided by the number that approached a fishway) at Bonneville Dam was 32%, the same as in 2007 (32%) but lower than previous telemetry study years (38%-48%). Efficiency estimates through sections of the fishway at Bonneville Dam were generally similar to or lower than in

previous years. Overall, Bonneville Dam passage efficiencies ranged from 51-68% through fishway entrance areas, 63-90% through the collection channels, 42–72% through transition pools, 70-96% through ladder sections, and 84-99% past count stations.

Median fishway passage times (the time from the first detection approaching a fishway entrance to the last detection at a top-of-ladder fishway exit) were 3.1 d at Bonneville Dam and 1.1 d at The Dalles Dam. Lamprey fallback percentages were high compared to previous years at both Bonneville (17%) and The Dalles (11%) dams; 33% fell back after passing John Day Dam.

Overall passage efficiency at The Dalles Dam was 68%. The majority initially approached the east shore entrance (33%), followed by the north shore (30%), west Powerhouse (21%), and south spillway (16%) entrances. The distribution of where lamprey entered The Dalles fishways was similar to the distribution of fishway approaches.

Lamprey behavior near Bonneville Dam count windows indicated that more than half the fish moved downstream past a window one or more times, typically after being detected in or near the serpentine weir sections of the ladders. Many of these fish subsequently exited fishways back into the tailrace.

Introduction

Populations of adult Pacific lamprey *Lampetra tridentata* in the Columbia River basin have declined precipitously from historic levels (Close et al. 2002). Lamprey abundance based on adult counts at hydroelectric dams has decreased four-to ten-fold during the past 40 years (Close 2001). As a result of these declines, petitions were recently submitted to list Pacific lamprey under the U.S. Endangered Species Act. In response, the U.S. Fish and Wildlife Service concluded that there was insufficient data on Pacific lamprey abundance, population trends, stock structure, and basic biology to support federal protection for the species (USFWS 2004).

Decreases in lamprey populations appear to be related to poor habitat conditions, low outmigration survival past dams, and other factors in both fresh and salt water life stages. Hydroelectric dams that can impede the upstream migration of adult Pacific salmon and steelhead (*Oncorhynchus* spp.) have also affected Pacific lamprey passage (Moser et al. 2002a, 2002b; Cummings 2007). Fishways at these dams were primarily designed to facilitate passage by adult salmon and steelhead and may not accommodate swimming abilities of adult lamprey. For example, adult lamprey passage efficiencies at lower Columbia River dams are often < 50% (Moser et al. 2005; Keefer et al. 2009) compared to adult salmon and steelhead passage efficiencies that are typically > 90% (e.g., Keefer et al. 2004). Concerns about low lamprey passage efficiencies have led to recent development of passage structures specifically for Pacific lamprey which have improved passage rates (e.g., Moser et al. 2006). However, radiotelemetry studies have suggested that adult lamprey have difficulty entering fishway entrances *en route* to the lamprey passage structures (LPS), particularly the northern-most fishway entrances at Bonneville Dam's Powerhouse 2 (PH2). It has been suggested that the high flow velocities at the entrances intended to attract adult salmonids and American shad (*Alosa sapidissima*) restrict lamprey entry (Moser et al. 2002; 2005; Daigle et al. 2005). Laboratory studies using PIT-tagged lamprey in an experimental fishway also indicated that high water velocity ($> 1.2\ m \bullet sec^{-1}$) can be a lamprey passage deterrent (Keefer et al. 2008).

A primary study objective in 2008 was to evaluate effects of zero head differential and fishway entrance success for radio-tagged lamprey at Bonneville Dam PH2 fishways. Additional 2008 study objectives addressed in this report include: (1) calculating lamprey passage efficiencies through segments of the Bonneville, The Dalles, and John Day fishways; (2) calculating lamprey passage times at the study dams; (3) assessing lamprey fishway entrance use patterns at the study dams; and (4) evaluating lamprey behaviors near the Bonneville Dam count windows. Several related migration-scale objectives were addressed in a separate report in combination with results from a concurrent half-duplex PIT-tagging study (see Keefer et al. *in review*).

Methods

Tagging and monitoring

In 2008, we radio tagged 595 adult lamprey at the Bonneville Dam Adult Fish Facility from 31 May through 18 August (Figure 1). Lamprey were captured at night using two traps installed in the Washington-shore fishway that collected lamprey as they passed over weirs and also by a trap located at the Washington-shore fishway entrance. Trapping at night increased capture efficiency because lamprey movements are more frequent during dusk and night (Almeida et al. 2002; Daigle et al. 2008). Night-time trapping also decreased the chance of interfering with adult salmonid passage. Lamprey with a girth circumference > 9 cm (at the insertion of the dorsal fin) were anesthetized in a 3 mL•50 L^{-1} solution of eugenol (the active ingredient in clove oil) and tagged with a uniquely-coded radio transmitter following protocols described in Moser et al. (2002) and Cummings (2007). We used Lotek NTC-4-2L radio transmitters (18.3 mm length, 8.3 mm diameter, and 2.1 grams in water) with a burst rate of 5 s and an expected tag life of 127 d (Lotek Wireless Inc. Newmarket, Ontario). Tagged fish were measured for length (mm), weight (g), and girth (mm) and evaluated for muscle lipid content (% fat) with a non-invasive Distell fish fat meter (Distell Inc., West Lothian, Scotland). Half the sample was double-tagged with a half-duplex passive integrated transponder tag (HDX-PIT; 4×32 mm and 0.8 g, Texas Instruments). Tissue samples were taken from the dorsal fin for eventual genetic analysis. After radio-tagged lamprey were fully recovered from anesthesia (< 2 hrs), they were randomly released ~3 kilometers downstream from the dam on either side of the river in approximately equal proportions.

Radio-tagged lamprey movements were monitored using an array of fixed-site receivers at Bonneville, The Dalles, and John Day dams (Figures 2 and 3). Radio receivers at the dams were equipped with digital spectrum processors (DSP's) to receive transmissions on a number of frequencies simultaneously. Radio receivers coupled with a scanning receiver and one or more underwater coaxial cable antennas were positioned at fishway entrances and inside fishways to detect when a fish first approached a fishway entrance, entered a fishway, moved within a fishway, and/or exited a fishway (note: only tailrace and top-of-ladder sites were monitored at John Day Dam). Telemetry data were downloaded from receivers weekly.

Velocity modification

PH2 fishway velocities at Bonneville Dam were manipulated by placing fish units on standy to float debris off of the trash racks. Shutting off fish units occurred only at night (typically between 2200 and 0430) to minimize potential effects on adult salmonid passage. Reductions of water levels to 0.0 ft head generally took < 5 min at the four main PH2 entrances (J. Rerecich, USACE, personal communication). Zero head differential was achieved by running two smaller turbine units (fish units) located in PH2 which were designed to provide water to the fishway collection channel. Four non-PH2 fishway entrances with higher velocities were always available for use by tagged lamprey during periods when the low velocity treatment was applied at PH2. Fishway entrances where normal velocities were always available included those at Powerhouse 1 (PH1) and the fishway entrances adjacent to the spillway (Figure 2).

Entrance efficiencies and passage times

We evaluated the total number of fishway approaches, entrances, and exits for adult lamprey at each fishway entrance in which the exact time of detection was known (including non-PH2 entrances). Unknown (i.e. exact time of passage was not known) approaches, entrances, and exits resulting from a missed antenna or receiver outages were excluded from this summary as were approaches, entrances and exits following a dam fallback event. In this way, we eliminated any bias in passage metrics that could result from including experienced fish.

We tested efficiency of the operational modifications at Bonneville Dam (i.e. zero head differential) by comparing experimental entrance efficiencies (the total number of lamprey that successfully entered a fishway entrance divided by the total number of lamprey that approached that same entrance) during a reduced water velocity treatment at four PH2 fishway entrances. To assess treatment effects, entries that occurred during a different treatment than the approach treatment were discarded. Fish that approached a fishway entrance but did not enter during a treatment were included in the percent unsuccessful. Experimental entrance efficiencies were calculated from 2200 to 0400 as in 2007 to facilitate between-year comparisons. We calculated entrance efficiencies pooled for all lamprey at each fishway entrance as well as entrance efficiencies for only first approaches and entries. We also calculated the net number of entries (i.e., number unique fish entering) by subtracting the total number of times fish exited a fishway from the total number of entries at each site. (Note: experimental entrance efficiency results were lower than efficiencies calculated in previous non-experimental studies as a result of discarding fish that approached and entered a fishway during opposite treatments. Caution should be used when comparing these entrance efficiencies to entrance efficiencies of previous non-experimental studies (pre 2007) which were calculated by dividing the total number of unique fish that entered a fishway by the total number of unique fish that approached).

For the fishway velocity experiment, passage times for radio-tagged lamprey were calculated for two segments at Bonneville Dam: (1) the fishway entry time, defined as the time between the first detection at an antenna along the outside of a fishway entrance to the first detection on the inside of a fishway entrance, and (2) total dam passage time, calculated from the first record on an antenna along the outside of a fishway entrance to the last record at a top-of-ladder site.

As part of the fishway use evaluations that were separate from the Bonneville Dam velocity test, we calculated lamprey passage times and passage efficiencies for a series of fishway segments at both Bonneville and The Dalles dams. These passage efficiencies were calculated differently than experimental passage efficiencies in that they were calculated by dividing the total number of unique lamprey that passed through each fishway entrance by the total number of unique lamprey that approached. Only total dam passage times were calculated at John Day Dam because only tailrace and top-of-ladder sites were monitored.

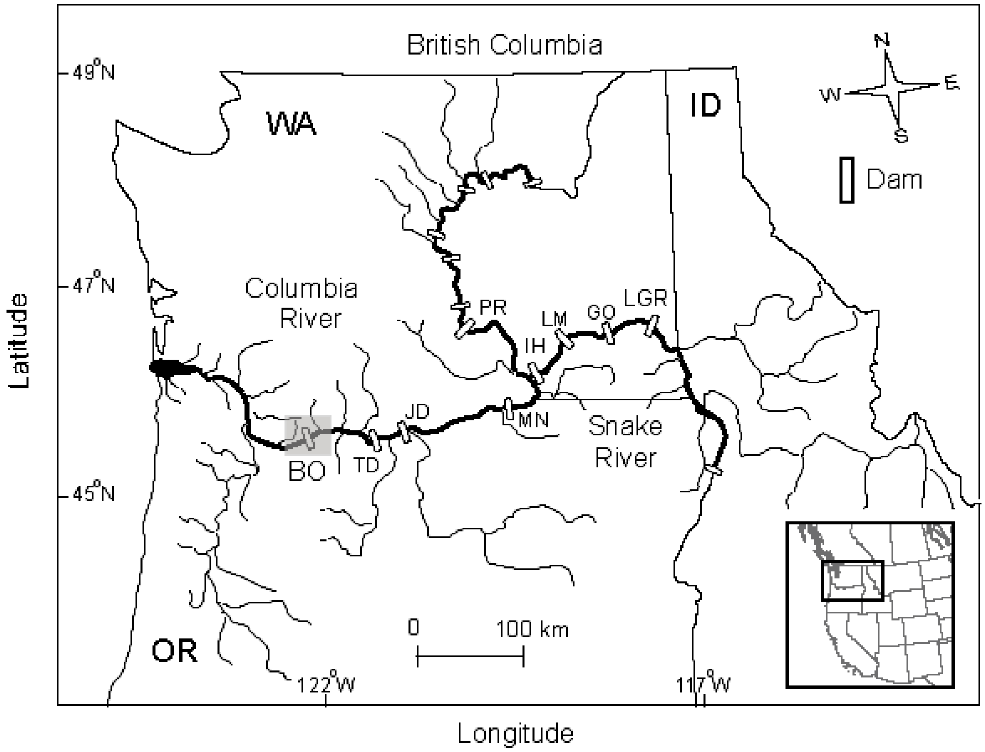

Figure 1. Map of the Columbia/Snake hydrosystem. Migrating adult lamprey were collected and radio-tagged at Bonneville Dam (shaded box).

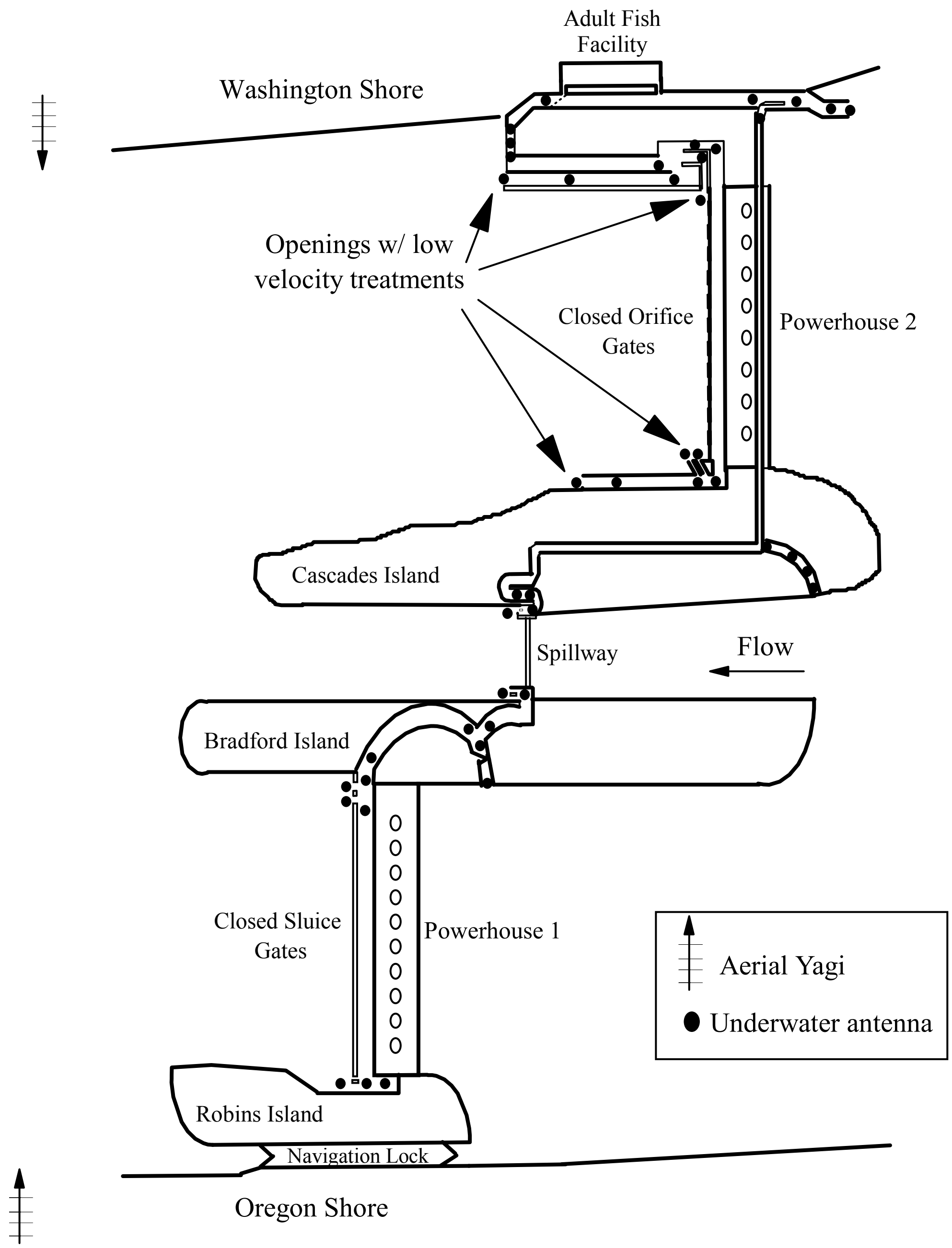

Figure 2. Aerial view of radio antenna deployments at Bonneville Dam during 2008 and fishway entrances where water velocities were being manipulated.

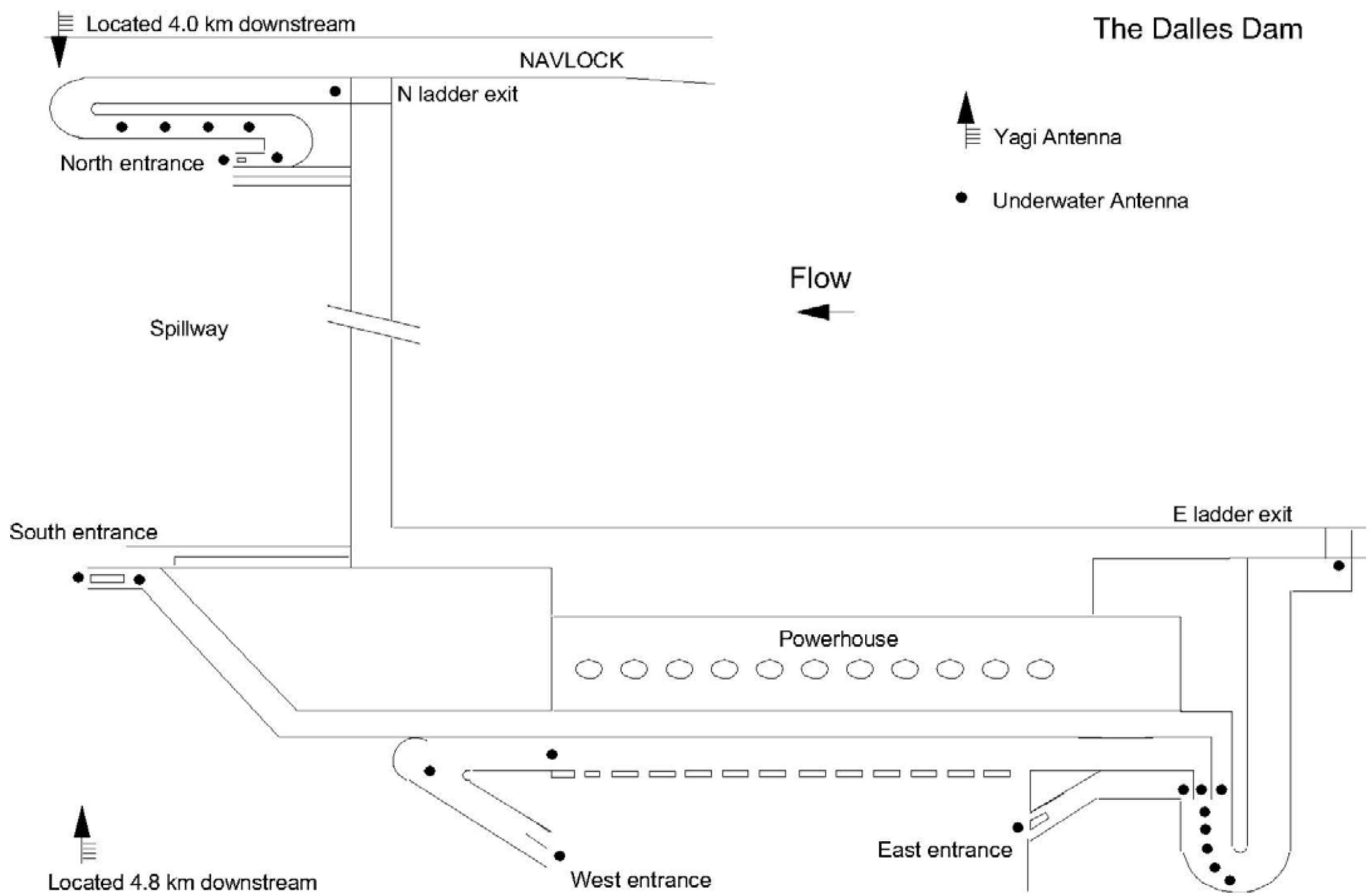

Figure 3. Aerial view of radio antenna deployments at The Dalles Dam during 2008.

Statistical analysis

Entrance efficiencies among Bonneville velocity treatments were compared using Pearson's χ^2 tests. We used a Yates continuity correction to adjust computed χ^2 values to compensate for one degree of freedom.

Multiple logistic regression was used to evaluate the probability of lamprey returning to Bonneville Dam after release downstream. In the logistic model, predictor variables were tag date, tag time, release site, total fish length, fish weight, percent girth of the radio tag relative to the fish, fat content, trapping location, presence of a HD PIT tag, and individual performing the surgery.

Results

Trapping and tagging

A total of 595 adult lamprey were radio-tagged and released (Figure 4). Lamprey were released at Tanner Creek (n = 283, 48%), approximately 3.1 km downstream from the dam on the Oregon shore, and at the Hamilton Island boat ramp (n = 312, 52%), approximately 3.6 km downstream from the dam on the Washington shore. Due to reduced lamprey abundance and lower CPUE (< 3 lamprey/hour) in 2008 we were unable to select for larger fish on a day-to-day basis as a strategy to minimize potential size-related tag effects, as was done in previous years (Figure 5). On average, lamprey radio-tagged in 2008 (as in 2007) were shorter, weighed less, and were smaller in diameter than those tagged in previous radiotelemetry studies (Table 1). In 2008, the mean radio tag wet weight was 0.45% (range 0.30-0.74%) of the lamprey body weight and 23.1% of the girth (range 19.3–27.9%; Figure 6). Mean time in anesthesia (total surgery time) for radio tagged lamprey was 9:50 min (*range* 6:29–19:00 min).

Table 1. Number of lamprey released below Bonneville Dam from 1997-2007 and in 2008, mean lamprey length and weight, number of lamprey detected at Bonneville Dam, proportion of tagged fish recorded passing the dam (% passage efficiency), the number of fish falling back over the dam (%), and the median travel time (days) to pass the dam. Pre-2008 data from Moser et al. (2002, 2003, 2004 and 2005) and Johnson et al. (2009).

	1997	*1998*	*1999*	*2000*	*2001*	*2002*	*2007*	*2008*
# Released	147	205	199	299	298	201	398	595
Mean Length (cm)	70	70	71	70	77	72	66	66
Range	60-80	59-79	65-78	62-80	62-82	60-80	53-86	49-79
Mean Weight (g)	-	545	571	570	588	612	466	464
Range	> 450	420-830	475-755	405-825	380-880	440-790	256-810	284-706
Detected at Bonneville	88%	89%	92%	87%	93%	96%	68%	74%
Passage Efficiency*	38%	40%	45%	47%	46%	48%	31%	32%
Fallback	< 1%	< 1%	2%	1%	-	1%	28%	17%
Median Dam Passage	4.9 d	5.7 d	5.5 d	4.4 d	11.0 d	9.0 d	3.0 d	3.8 d

* navigation lock not monitored in 2007 and 2008.

Return to Bonneville Dam

Of the 595 tagged lamprey, 443 unique fish (74%) were recorded approaching Bonneville Dam fishway entrances (Table 1). In the logistic regression analysis, tag date ($P = 0.01$) and total fish length ($P = 0.02$; Figure 7) were associated with the likelihood of fish returning to Bonneville Dam (Table 2). Fish tagged later in the year were less likely to return to the dam as were shorter fish. Three-hundred and eighteen fish (53%) entered a fishway, and 156 (26% of total radio-tagged) passed the dam (Table 1).

Table 2. Details of the logistic regression. Significant ($P < 0.05$) terms indicated in bold.

Variable	*Coefficient*	*Standard Error*	*P value*
trap location	0.28	0.16	0.09
tagger	0.15	0.09	0.08
% fat	-0.06	0.04	0.17
% girth	0.09	0.14	0.52
fish weight	0.00	0.004	0.97
total length	**0.12**	**0.05**	**0.02**
presence of HD PIT	-0.15	0.20	0.47
release site	0.25	0.20	0.21
tag time	1.47	1.23	0.23
tag date	**-0.02**	**0.006**	**0.01**

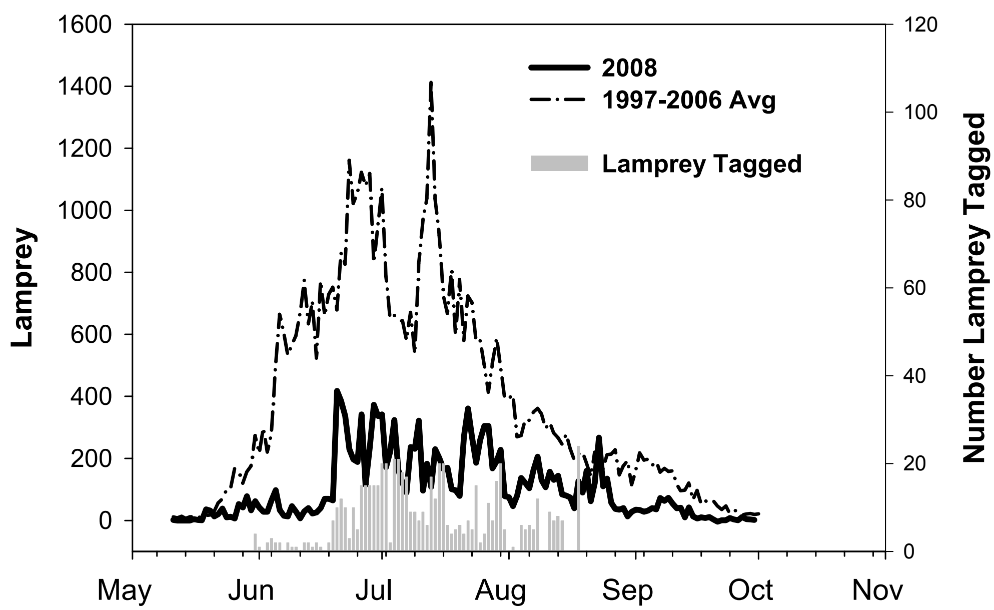

Figure 4. Counts of adult Pacific lamprey passing Bonneville Dam and the numbers collected and radio-tagged at the dam.

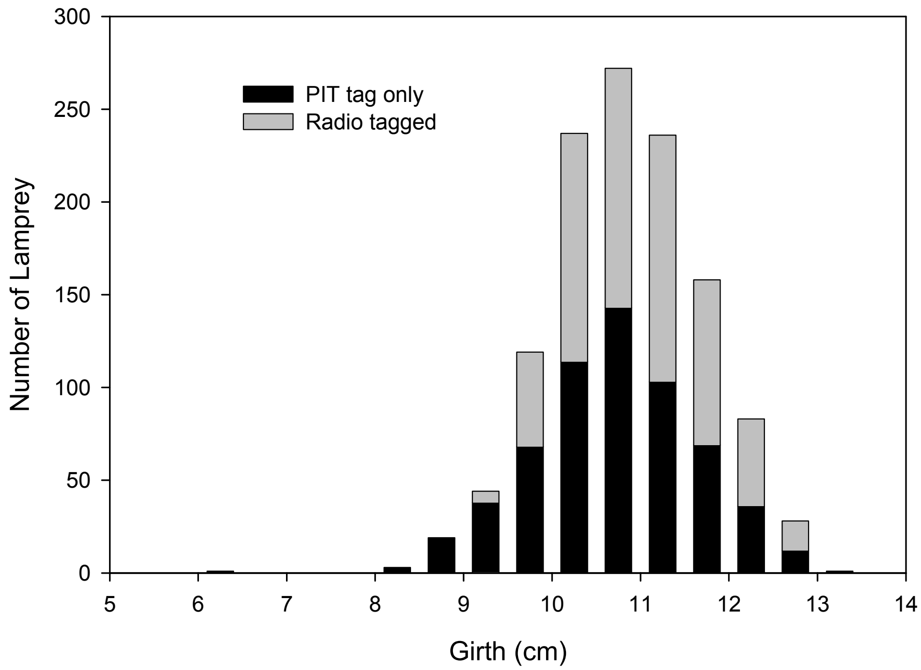

Figure 5. Distribution of girth measurements (taken just anterior to dorsal fin insertion) for lamprey HD PIT-tagged at Bonneville Dam (black bars), and tagged with radio transmitters (gray bars). Mean for lamprey HD PIT-tagged = 10.7 cm and mean for lamprey radio-tagged = 10.9 cm.

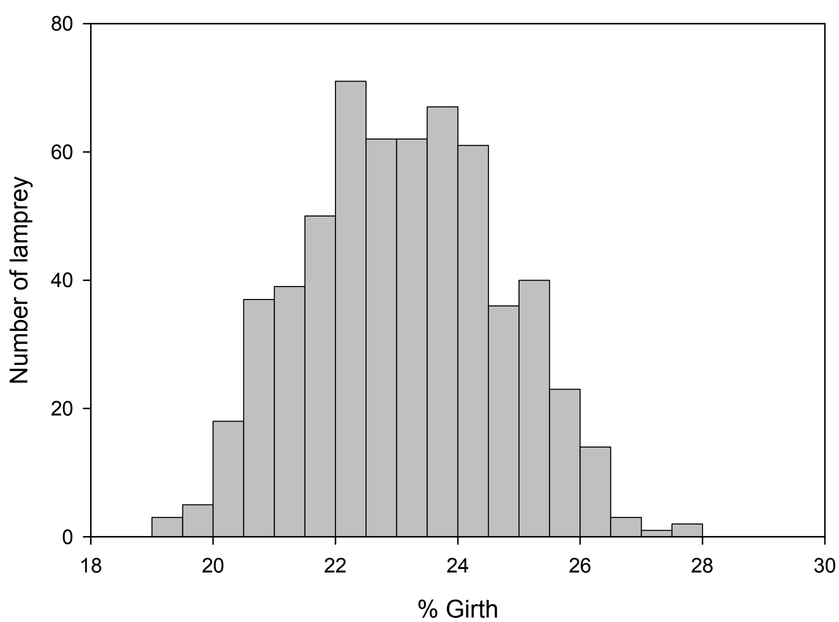

Figure 6. Frequency distribution of percent girth for radio transmitter size. Percent girth was calculated as transmitter circumference (cm) / lamprey circumference (cm) at insertion of anterior dorsal fin (cm) *100. Mean percent girth was 23.1% (range 19.3–27.9%).

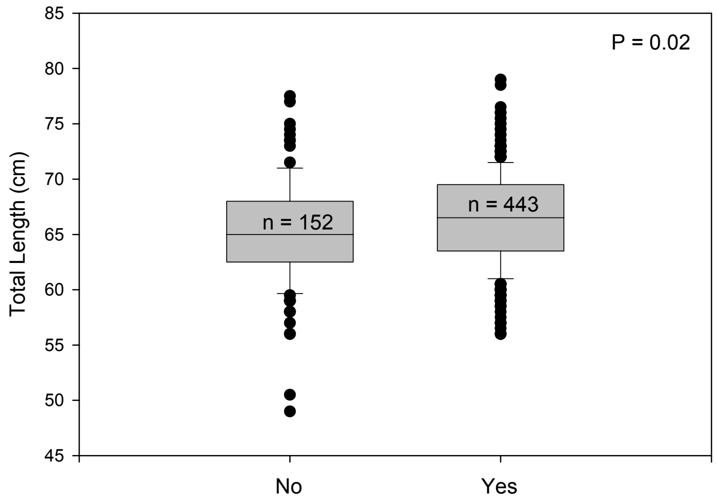

Figure 7. Median (horizontal lines within boxes), quartiles (upper and lower bounds of boxes), 10th and 90th percentiles (ends of whiskers) of lamprey total length that successfully returned to Bonneville Dam (Yes) and those that did not successfully return (No). Solid circles are individual outliers. Unsuccessful fish: median length = 65 cm, mean length = 65.2 cm. Successful fish: median length = 66.5 cm, mean length 66.6 cm.

First Approach and Entry Locations

Of the 443 unique lamprey that approached Bonneville Dam, 317 fish eventually entered a dam fishway. The majority of lamprey made first approaches at PH2 fishway openings (56%) followed by PH1 (30%) and the spillway (14%; Figure 8). There was a disproportionately low number of entries at PH2 north fishway openings and disproportionately high number of entries at PH2 south entrances (Figure 8). The proportion of fish that first entered the same fishway as they first approached ranged from 52.7% at PH2 north to 91.7% at PH1 north (Table 3).

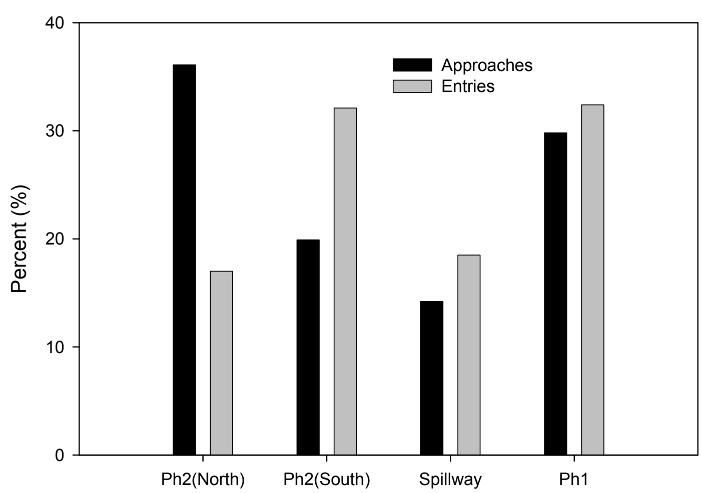

Figure 8. Distribution of first fishway approach and first entry sites for radio-tagged lamprey at Bonneville Dam (*n* = 443 approaches and 317 entries).

Table 3. Locations of first lamprey fishway entries, by the location of their first fishway approach site at Bonneville Dam in 2008.

First Approach Site		*First Entry Site*											
		PH1		Spillway			PH2				unknown		
		(south)	(north)	(south)	(north)	XBO[1]	(south)	(north)	MBO[1]	RBO[1]	OBO[2]	total	% same approach & entry
PH1													
(south)	4BO	42	19	3	1	0	4	0	0	0	0	69	60.9
(north)	8BO	2	33	1	0	0	0	0	0	0	0	36	91.7
Spillway													
(south)	BBO	0	0	21	1	1	0	0	0	1	0	24	87.5
(north)	CBO	0	0	0	7	1	2	0	0	0	0	10	70.0
	XBO	0	0	0	0	2	0	0	0	0	0	2	100
PH2													
(south)	DBO	1	2	3	1		44	8	5	2	0	66	66.7
(north)	LBO	1	3	9	5	0	49	8	15	3	0	93	52.7
	MBO	0	0	0	0	0	0	0	8	0	0	8	100
	RBO	0	0	1	1	0	2	3	1	0	0	8	0
(unknown)	OBO	0	0	0	0	0	0	0	0	0	1	1	100
Total		46	57	38	16	4	101	19	29	6	1	317	

[1]XBO is located inside the north spillway entrance and indicates entry at the north spillway fishway. MBO and RBO are located inside the north PH2 entrances and indicate entry at a PH2 north fishway.
[2]OBO is located near UMT channel in Washington shore fishway and is associated with unknown entrance location.

Bonneville velocity test

During the period 31 May through 1 October there were 70 nights (average 3.8 hrs per night) of reduced velocity (0.0’ head differential) at PH2 north and south fishway entrances as a result of placing fishway units on standby and 54 nights of normal operation (Figures 9 and 10).

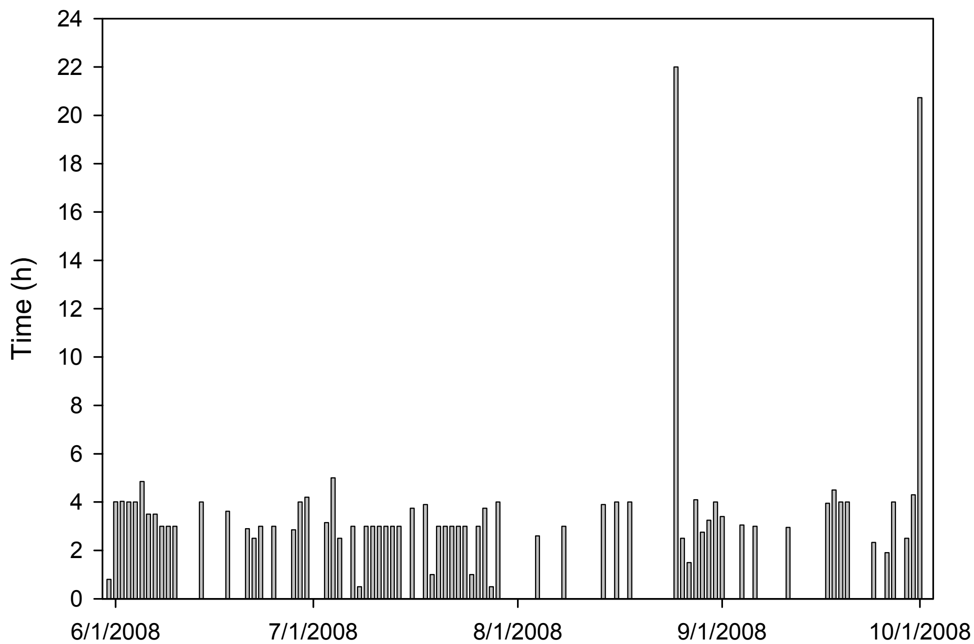

Figure 9. Total time that PH2 fishway units were placed on standby resulting in zero head differential at PH2 fishway entrances (reductions typically occurred between 2000 and 0430).

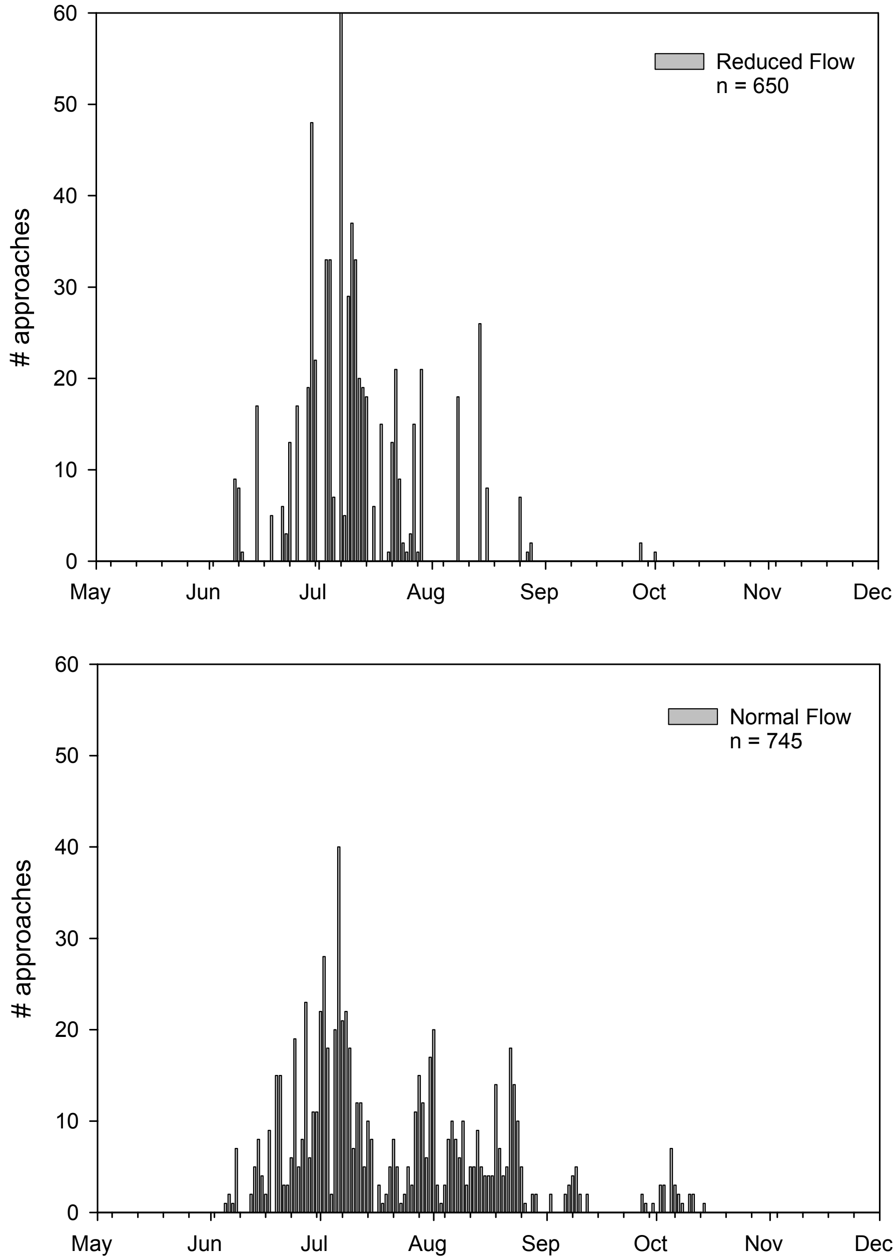

Figure 10. Total number of approaches made at PH2 fishways during the hours of 2000-0430 normal operation (bottom panel) and when fishway units were place on standby (top panel).

First approach and entry: PH2 north fishway – Of the 443 radio-tagged lamprey recorded at the dam, 248 (53%) made their first fishway approach at PH2 (Table 4). A total of 160 fish (36% of the 443 returning) made their first approach at PH2 north fishway entrances. Of the 152 fish (with known times) that first approached at a north PH2 fishway entrance, 107 made their first fishway approach at a north PH2 fishway entrance during normal operation and 45 made their first approach when PH2 fish units were running in standby (Table 4). Entrance efficiencies for fish making first approaches during normal velocities was < 1% (1 entry out of 107 that approached) and 4% (2 entered out of 45 that approached) when fish units were in standby operation (Table 4). The percentage of fish entering PH2 north entrances when PH2 fish units were in standby operations (4%) was not significantly higher (Pearson's $\chi^2 = 0.56$, $P = 0.45$) than the proportion entering during normal operation (< 1%). However, the power for this test (0.108) was below desired power (0.80) suggesting that sample sizes were too small to detect a difference.

First approach and entry: PH2 south fishway – A total of 88 fish (20% of the 443 returning; Table 4) made their first approach at PH2 south fishway entrances (76 with known times). Across velocity treatments, 13 of the 76 lamprey that made their first approach at a PH2 south fishway followed with successful entries (17.1 % entrance efficiency). Of the 76 fish that first approached at a south PH2 fishway entrance, 55 made their first fishway approach at a south PH2 fishway entrance during normal operation and 21 made their first approach when PH2 fish units were running in standby (Table 4). Entrance efficiencies at this site were 18% (10 entries out of 55 approaches) during normal velocities and 14% (3 entries out of 21 approaches) during standby operation (Table 4). Entrance efficiency did not differ between operations (Pearson's $\chi^2 = 0.00$, $P = 0.98$).

First approach and entry non-PH2 fishways – Forty-four percent of lamprey recorded at the dam made their first approach at non-PH2 fishway entrances: 14% approached entrances adjacent to the spillway and 30% approached PH1 entrances (Table 4). Entrance efficiencies at non-PH2 fishways for fish making their first approach and entry were 42% at the spillway entrances and 43% at PH1 fishway entrances (Table 4).

Table 4. Distributions of known first fishway approaches and entries and estimated entrance efficiencies for radio-tagged lamprey at Bonneville Dam in 2008. Shaded cells are for the PH2 fishway entrances during normal and standby operation.

	Percent of total (n)							
				PH2 South			*PH2 North*	
	PH1	Spillway	PH2 south[1]	Normal	Standby	PH2 north[1]	Normal	Standby
Approaches	30.0% (132)	13.6% (60)	20.0% (88)	72.4% (55)	27.6% (21)	36.4% (160)	70.4% (107)	29.6% (45)
Entries	48.3% (57)	21.2% (25)	21.2% (25)	76.9% (10)	23.1% (3)	9.3% (11)	33.3% (1)	66.7% (2)
Entrance Efficiency[2]	43.2%	41.6%	28.4%	18.2%	14.3%	6.9%	< 1%	4.4%

[1] Includes fish with known entrance location but unknown entrance time
[2] Entrance efficiency = total # first entries / total # first approaches at same entrance

Total approach and entry: PH2 north fishways – Two-hundred and fifty-five lamprey made a total of 1,406 approaches at a north PH2 fishway entrances (Table 5). A total of 893 approaches were between the hours of 2200 and 0400 (443 during normal velocity by 158 unique fish and 450 during the standby operation by 118 unique fish; Table 6). Proportionately more fish approaches were followed by entries during the normal velocity treatment (9%) than during the standby operation treatment (2%) (Pearson's $\chi^2 = 14.8$, $P < 0.001$; Table 6). Entrance efficiencies increased at the upstream-most entrance to PH2 north (adjacent to the face of PH2) from < 1% to 7% during normal velocity and from 5% to 11% at the downstream-most entrance to PH2 north (Figure 11). We recorded a net gain of 20 entries at PH2 north during normal operation (second highest after PH1) and a net loss when fish units were running on standby (Table 6).

Table 5. Total numbers of approaches, entries, and exits pooled for all fish, entrance efficiencies (total number of entries divided by total number of approaches), and the net number of entries (total number of entries – total number of exits) at Bonneville Dam in 2008.

	Total	*PH1*	*Spill*	*PH2 south*	*PH2 north*	*Unknown (location)*
Approaches	2,833	15% (428)	9% (257)	24% (687)	50% (1,406)	2% (55)
Entries	587	25%(145)	15% (90)	36% (212)	14% (81)	10% (59)
Efficiency	21%	34%	35%	31%	6%	na
Exits	440	19% (82)	15% (68)	47% (205)	15%(65)	4% (20)
Net	**147**	**63**	**22**	**7**	**16**	**39**

* Entrance efficiency = total # entries / total # approaches at same entrance.

Table 6. Total numbers of approaches, entries, and exits pooled for all fish, entrance efficiencies (total number of entrances divided by total number of approaches), and the net number of entries (total number of entries – total number of exits) at Bonneville Dam between the hours of 2200-0400.

					PH2 South			*PH2 North*	
	Total	PH1	Spill	PH2 south	Normal	Standby	PH2 north	Normal	Standby
Approaches	1587	12% (201)	8% (120)	24% (371)	48% (179)	52% (192)	56% (893)	50% (443)	50% (450)
Entries	232	28% (64)	19% (43)	33% (77)	70% (54)	30% (23)	20% (48)	79 % (38)	21 % (10)
Efficiency	15%	32%	36%	21%	30%	12%	5%	9%	2%
Exits	170	21% (35)	21% (36)	37% (63)	63% (40)	37% (23)	21% (36)	50% (18)	50% (18)
Net	**62**	**29**	**7**	**14**	**14**	**0**	**12**	**20**	**-8**

Total approach and entry: PH2 south fishway – Two-hundred and sixteen lamprey made a total of 687 approaches at a south PH2 fishway entrance (Table 5). A total of 371 approaches were made between 2200 and 0400 (179 during the normal velocities by 111 unique fish and 192 during standby operation by 90 unique fish; Table 6). Entrance efficiencies between 2200 and 0400 were 30% during normal velocity and 12% during standby operation (Table 6).

Efficiencies between 2200 and 0400 were significantly higher during normal velocities (Pearson's $\chi^2 = 11.4$, $P < 0.001$). Entrance efficiencies increased during normal velocities at the upstream-most entrance to PH2 south (adjacent to the face of PH2) from 11% to 29% and from 22% to 50% at the downstream-most entrance to PH2 north (Figure 11). We observed no net gain of fish when fish units were running on standby at PH2 south and a net gain of 14 fish during normal operation (Table 6).

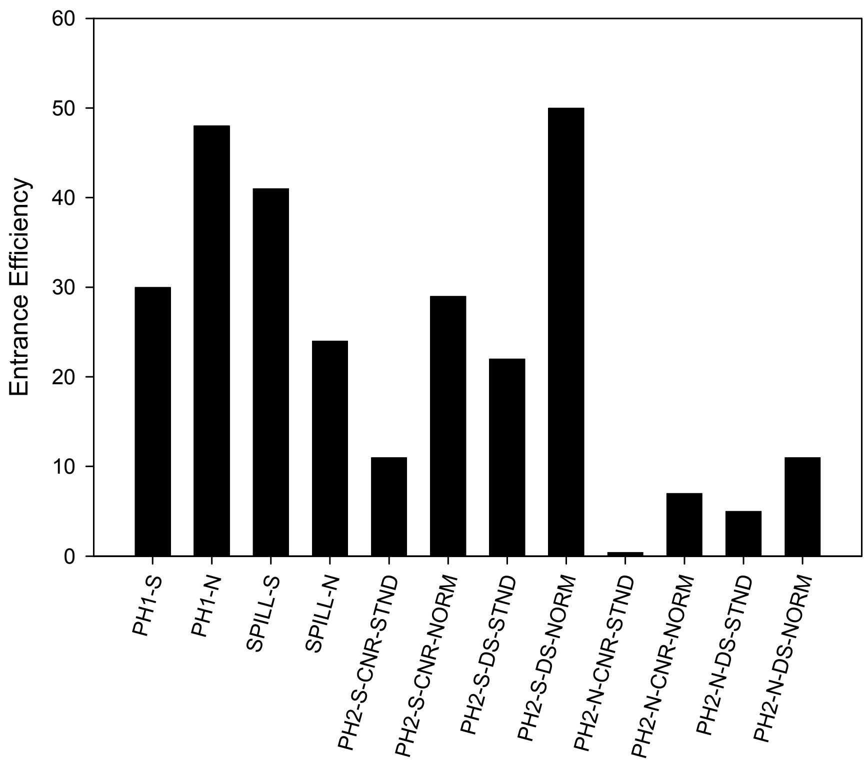

Figure 11. Entrance efficiency (total # entries / total # approaches at same entrance) during the hours of 2200-0400 at each of the Bonneville Dam fishway entrances from south (S) to north (N) along Powerhouse 1 (PH1), the spillway (SPILL), and Powerhouse 2 (PH2). Main entrances at PH2 included those downstream (DS) and in the corners (CNR) during the normal (NORM) and standby (STND) fishway operations.

Total approach and entry: non-PH2 fishways – A total of 685 approaches were made at non-PH2 fishway entrances (i.e. spillway and PH1) by 276 unique lamprey (Table 5). Of the 685 approaches, 235 resulted in entries (34% entrance efficiency) by 177 unique lamprey (Table 5). Entrance efficiencies at non-PH2 fishway entrances were 34% at PH1 and 35% at the spillway entrances (Table 5). Forty-seven percent (321/685) of the approaches at non-PH2 fishway entrances were made between 2200 and 0400, resulting in passage efficiencies ranging from 32% at PH1 to 36% at the spillway entrances (Table 6). We recorded a disproportionately greater number of exits at PH2 north and south entrances compared to other fishway entrances, particularly during standby operation (Tables 5 and 6).

Passage times – The median time from first fishway approach to first fishway entry for all radio-tagged lamprey at Bonneville Dam was 1.5 h and ranged from 0.4 h for lamprey that entered PH1 and spillway fishways to 2.0 h for fish that entered fishways at the north end of PH2 (Table 7). Entry times were substantially longer during normal velocity times at PH2 north and PH2 south (*median* = 1.6 h) compared to standby velocities (*median* = 0.7 h and 0.5 h, respectively; Table 7). Treatment comparisons were limited to night, while the total passage times included daytime entries.

The median time to pass the dam for lamprey that entering during normal velocity at PH2 was 2.3 d (n = 37) versus 4.5 d for 4 lamprey that entered during the standby operation (Table 7). Few fish were detected at mid-ladder telemetry sites during daylight hours (Figure 12). Lamprey arriving mid-ladder before midnight generally passed the dam within a few hours. Conversely, about half of the fish that arrived mid-ladder after midnight passed the following evening.

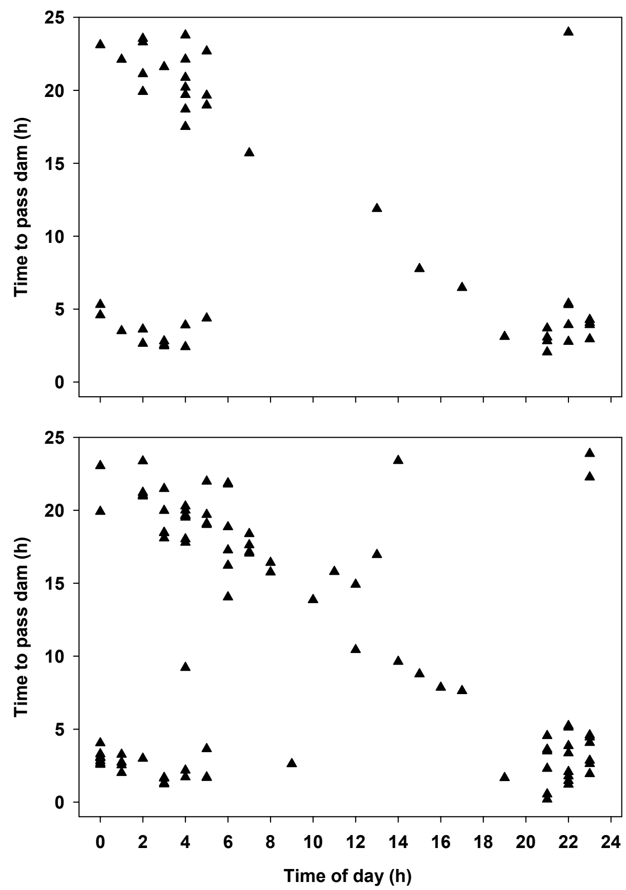

Figure 12. Passage times for radio-tagged lamprey in the upper half of the Bradford Island fish ladder (just upstream of where fish ladder converge to the top of the ladder) top panel and Washington shore (just upstream of UMT channel to top of the ladder) bottom panel relative to the time of arrival at the half-way point.

Table 7. Median fishway entry times (top) and dam passage times (bottom) for lamprey that first approached and entered Bonneville Dam. Washington shore dam passage times included fish that entered both south and north PH2 entrances.

	Median Time (n)							
				PH2 South			PH2 North	
	PH1	Spill	PH2 South	Normal	Standby	PH2 North	Normal	Standby
Approach to Entry	0.4 h	0.4 h	1.4 h	1.6 h (49)	0.5 h (7)	2.0 h	1.6 h (15)	0.07 h (5)
Range	8 s – 15 d	18 s – 35 d	6 s – 105 d	12 s – 105 d	6 s – 2.8 h	2 s – 9 d	5 min – 9 d	2 s – 23.4 h

	Median Time (n)				
				Washington Shore	
	Bradford Ladder	Bradford AWS*	Combined	Normal	Standby
Time to Pass Dam	1.7 d (35)	2.3 d (10)	2.3 d (41)	2.3 d (37)	4.5 d (4)
Range	8.2 h – 51 d	18.6 h – 14 d	7.4 h – 62d	7.4 h – 62d	2.3 d – 9 d

*AWS = auxiliary water supply.

Bonneville fallbacks

We recorded 26 unique lamprey (17% of the total that passed the dam) falling back over the dam (Table 1). Sixty-five percent (17 of 26) of the fallback events occurred after fish exited the Bradford Island fishway, and 35% occurred after fish exited the Washington-shore fishway. Fallback percentages (number of fallback fish divided by the number recorded passing) were 21.5% for fish exiting the Bradford Island fishway and 14.3% for fish exiting the Washington-shore fishway. The median number of days between exiting the fishway and being detected downstream from the dam was 12.7 d (*range* = 5.8 h–33.0 d). Average spill percent (% of total dam outflow at the spillway) was 50.6% during times radio-tagged fish fell back and 51.2% for fish that didn't fall back. Eighteen of the fish (69%) that fell back were last recorded in the Bonneville Dam tailrace, three (12%) were last recorded at underwater antennas at Bonneville Dam fishway entrances, four (15%) had last records in the Columbia River downstream from the release sites (rkm 206-223), and one (4%) was in the Willamette River downstream from Willamette Falls Dam.

Bonneville fishway use

Passage efficiency – Of the 595 tagged lamprey, 443 (74%) were recorded approaching Bonneville Dam fishway entrances, 318 (53%) entered a fishway, and 156 (26%) passed the dam (Table 1). Estimated passage efficiencies through segments of the fishways were within the range calculated at Bonneville Dam in the earlier (1997–2007) telemetry studies, except that efficiencies were lower at PH1 and PH2 entrances and transition pool sections than in previous years (Table 8). Passage efficiencies were also lower in the spillway transition and ladder segments. Overall, passage efficiencies ranged from 51- 68% through fishway entrance areas, 63-90% through the collection channels, 42-72% through transition pools, 70-96% through ladders, and 84-90% through the count stations (Table 8).

Table 8. The number of unique radio-tagged lamprey that passed through each area within each fishway at Bonneville Dam in 1997-2002 (as reported in Moser et al. 2005), 2007 (as reported in Johnson et al. 2009), and in 2008. Passage efficiency (number of lamprey that passed through the area/number of unique lamprey that approached or entered the area × 100) is in parenthesis.

	Year							
Area	1997	1998	1999	2000	2001	2002	2007	2008
				PH1				
Entrance[1]	47 (60%)	78 (80%)	63 (72%)	97 (74%)	71 (74%)	54 (76%)	44 (76%)	106 (68%)
Collection	36 (77%)	63 (81%)	55 (87%)	85 (88%)	59 (83%)	41 (76%)	29 (66%)	78 (74%)
Transition	32 (89%)	61 (97%)	50 (91%)	82 (96%)	58 (98%)	38 (93%)	26 (90%)	56 (72%)
Ladder	27 (78%)	59 (97%)	49 (98%)	71 (86%)	52 (90%)	35 (92%)	25 (96%)	54 (96%)
Count station[2]	21 (78%)	37 (63%)	38 (78%)	63 (89%)	45 (86%)	25 (71%)	25 (83%)	59 (84%)
				PH2				
Entrance[1]	50 (69%)	78 (81%)	87 (80%)	109 (78%)	100 (85%)	157 (77%)	114 (67%)	165 (61%)
Collection	30 (60%)	50 (64%)	79 (79%)	63 (72%)	94 (60%)	84 (77%)	66 (58%)	104 (63%)
Transition	25 (83%)	32 (64%)	43 (54%)	43 (68%)	72 (77%)	54 (64%)	30 (45%)	50 (48%)
Ladder	24 (96%)	29 (91%)	43 (100%)	38 (88%)	71 (99%)	52 (96%)	29 (97%)	35 (70%)
Count station[2]	21 (88%)	25 (86%)	35 (81%)	32 (84%)	57 (80%)	42 (81%)	39 (98%)	91 (99%)
				Spillway				
Entrance[1]	33 (54%)	35 (44%)	41 (57%)	69 (60%)	55 (65%)	66 (62%)	57 (54%)	77 (51%)
Collection	19 (58%)	21 (60%)	22 (54%)	63 (91%)	53 (96%)	59 (89%)	51 (89%)	69 (90%)
Transition	14 (74%)	12 (57%)	11 (50%)	37 (59%)	39 (74%)	37 (63%)	26 (51%)	29 (42%)
Ladder	11 (79%)	11 (92%)	10 (91%)	32 (86%)	36 (92%)	35 (95%)	19 (73%)	21 (72%)
Count station[2]	6 (54%)	9 (82%)	8 (80%)	24 (75%)	26 (72%)	25 (71%)	32 (94%)	21 (88%)

1 Entrance efficiency = total # unique entries / total # unique approaches. These efficiencies don’t take into treatment switching or multiple approaches.

[2] count window efficiencies is the number detected on the antenna above the count window / number detected on the antenna downstream of the count window

Passage success – Of the radio-tagged lamprey that entered and successfully passed the dam, passage success was highest for those fish that entered PH1 fishway entrances (55.9%) and lowest for those using PH2 entrances (39.5%), particularly those fishway entrances at the south end of PH2 which had a combined passage efficiency of 34.5% (Table 9).

Table 9. Passage success (entrance to top-of-ladder) for radio-tagged lamprey based on location of first fishway entrance.

Location	*Site*	*Antenna*	*Entrances*	*Last Tops*	*Percent*
PH2 South	DBO	1	4	1	25.0
PH2 South	DBO	5	54	19	35.2
PH2 South	DBO	Both	58	20	34.5
PH2 North	LBO	1	8	3	37.5
PH2 North	LBO	5	15	9	60.0
PH2 North	LBO	Both	23	12	52.2
PH2	Combined	All	81	32	39.5
PH1 South	4BO	1	46	27	58.7
PH1 South	8BO	1	13	6	46.2
PH1	Combined	Both	59	33	55.9
Spill South	BBO	1	38	17	44.7
Spill North	CBO	1	14	7	50.0
Spill	Combined	Both	52	24	46.2

We also summarized dam passage efficiency by receiver location (Figure 13). In this analysis, the percentage of tagged lamprey that passed the dam was calculated by dividing the total number of fish recorded at each receiver (at any time) by the number that subsequently passed the dam. Receiver sites often included several individual antennas at each location. Results indicated that lamprey were increasingly likely to pass the dam the further up the fishway they were recorded. For example, 42-53% of the fish recorded at the receivers used to monitor the entrances at the north and south ends of PH1 (8BO and 4BO) eventually passed the dam; percentages increased to 71% for those detected in the Bradford Island transition pool (VBO), to 83% at the mid-point of the Bradford Island fishway (9BO), and to 98% at the receiver near the top of the ladder (ABO) (Figure 13).

Lamprey that entered the south-spillway entrance (BBO) and transition pool (WBO) or the north-spillway entrance (CBO) and transition pool (XBO) were among the least likely to pass the dam. Dam passage efficiencies for these fish were 27-37% for those detected at the entrance receivers. Similarly, lamprey recorded at the Cascades Island makeup water channel (FBO and GBO) were relatively unlikely to be recorded passing the dam.

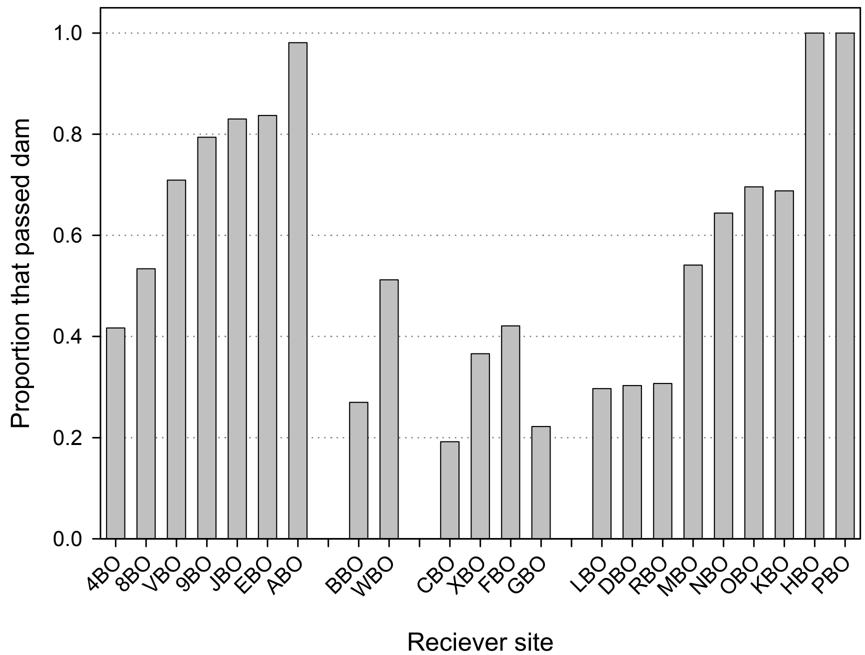

Figure 13. Proportion of radio-tagged lamprey that passed Bonneville Dam based on receiver site detections. Site locations: PH1 entrances and transition pool (4BO, 8BO, VBO), Bradford Island ladder (9BO, JBO, ABO), Bradford Island makeup water channel (EBO), south spillway entrance and transition pool (BBO, WBO), north-spillway entrance and transition pool (CBO, XBO), Cascades Island makeup water and UMT channel (FBO, GBO), PH2 entrances and transition pool (LBO, DBO, RBO, MBO), Washington-shore ladder (NBO, OBO, KBO, PBO), and Washington-shore makeup water channel (HBO).

Washington shore – In 2008, 71 radio-tagged lamprey approached the count station (antenna KBO3) and 69 (97%) entered the serpentine weir section (KBO5) upstream of the count window (Figures 14-15). Of the two fish that did not pass KBO5, one moved downstream and entered the makeup water channel and exited the top of the ladder and the other moved back down the ladder and exited into the tailrace through a PH2 entrance. Of the 69 lamprey that entered the serpentine weir section, 3 (4%) crossed into the makeup water channel and exited the top of the ladder (while remaining on the makeup water channel side of the ladder). Twenty-five (36%) moved back down the ladder and exited the ladder into the tailrace through spillway (44%), PH2 (28%) or Cascade Island (28%) entrances. The remaining 41 (59%) fish (of the 69 that entered the serpentine weir) moved upstream past the serpentine weirs and exited the top of the fish ladder. The four lamprey that crossed into or entered the makeup water channel resided there for a median time of 1.5 h.

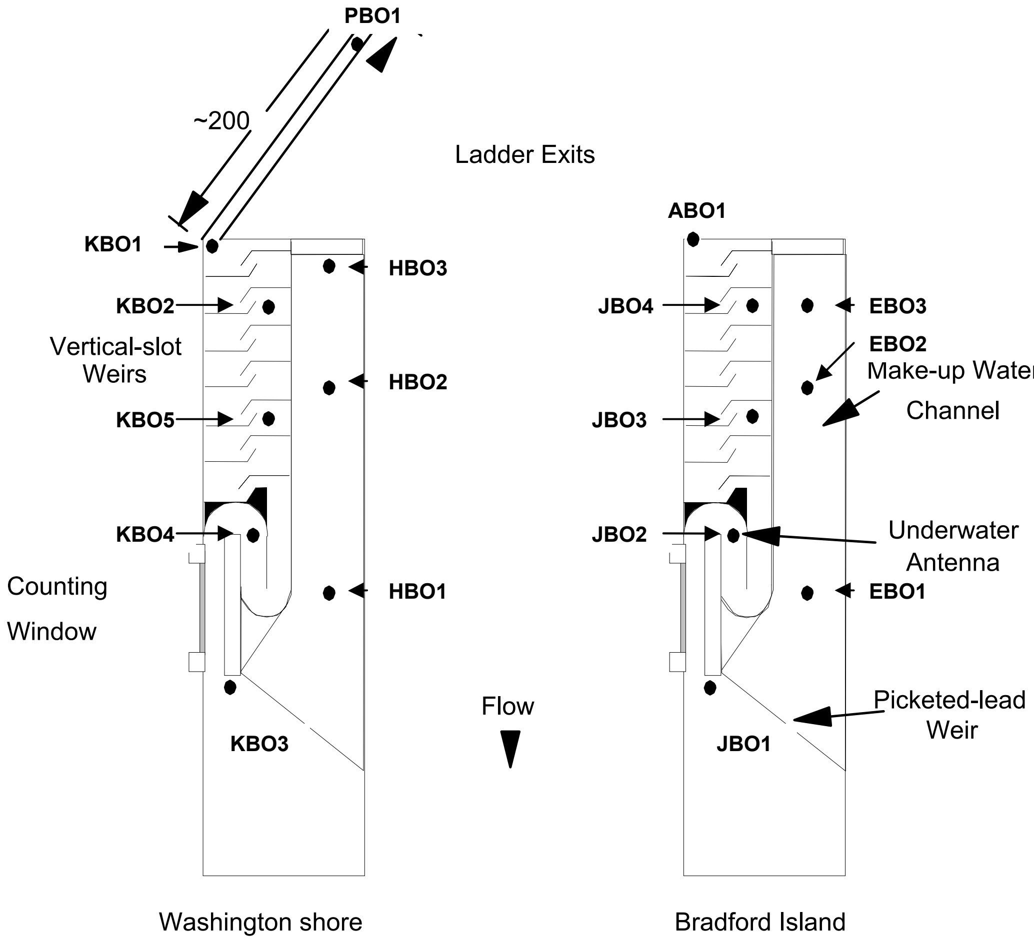

Figure 14. Aerial view of radio antenna deployments at the Bonneville Dam count stations during 2008.

Bradford Island – In 2008, 93 radio-tagged lamprey approached the count station (antenna JBO1) and 82 (88%) entered the serpentine weir section (JBO3) upstream from the count window (Figure 15). Of the 82 lamprey that entered the serpentine weir section, 16 (20%) crossed into the makeup water channel and exited the top of the ladder (while remaining on the makeup water channel side of the ladder). Fifteen (18%) of the 82 moved back down the ladder and exited the ladder into the tailrace through spillway (47%), PH2 (47%) or Cascade Island (6%) entrances. The remaining 51 (62%) fish (of the 82) moved upstream past the serpentine weirs and exited the top of the fish ladder. Of the 82 fish that entered the serpentine weir section, a total of 30 fish (37%) had hits on makeup water channel antennas (EBO): 16 (53%) fish that crossed over to the makeup water channel, 6 (20%) that moved back down the ladder and exited into the tailrace, and 8 (27%) fish that moved through the serpentine weirs and exited the top of the fish ladder.

Thirteen fish went through the picket lead gate into the makeup water channel. Of the 13, 11 (85%) moved upstream through the makeup water channel and exited the ladder. The remaining two fish moved downstream, one to JBO1 and then back up the makeup water channel and to the top of the ladder, and one that moved down the ladder and exited into the tailrace through the south spillway entrance. Lamprey that directly entered (n = 13) or crossed over (n = 16) to the makeup water channel resided there for a median of 3.1 h.

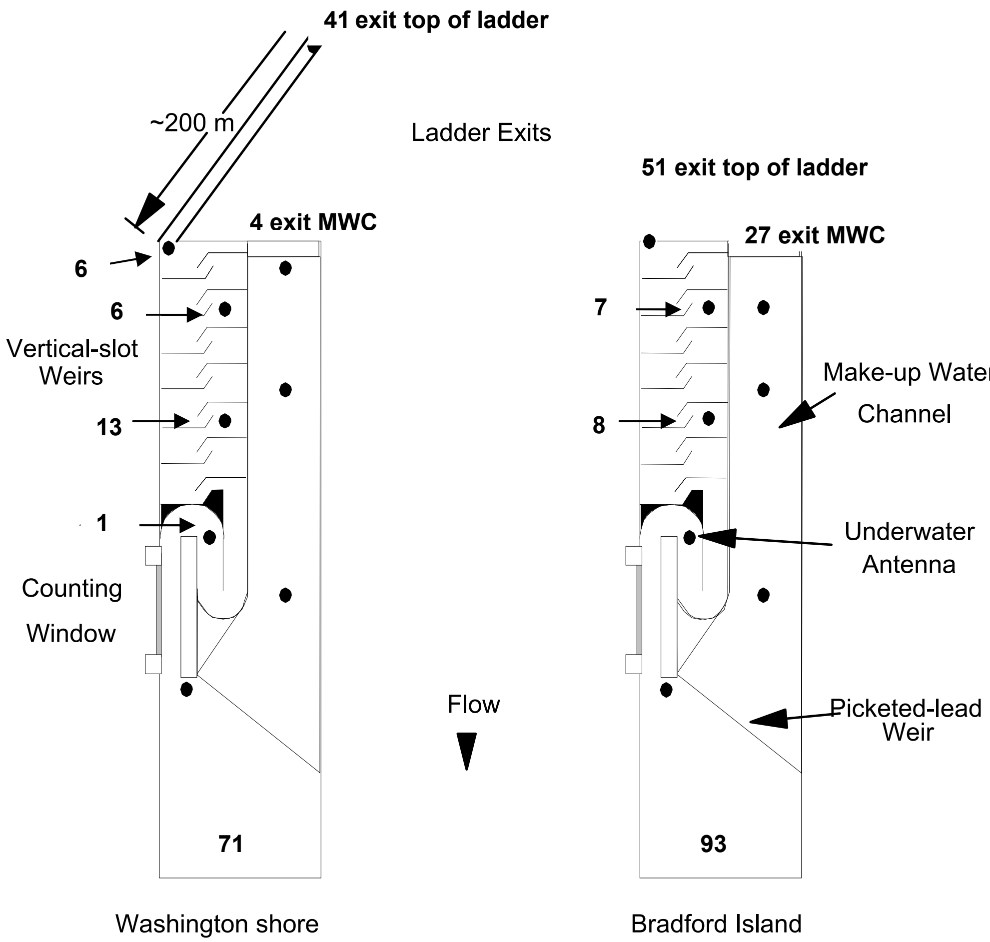

Figure 15. Most upstream detections of the radio-tagged lamprey that approached the count stations in the Washington-shore (left panel, n = 71) and the Bradford Island (right panel, n = 93) ladders. Solid circles represent the positions of antennas and the numbers at each site indicate the number of lamprey for which that antenna was the furthest upstream detection point. Numbers at the top of the diagram indicate the number of lamprey that exited each fishway into the forebay.

Behavior near count windows – A total of 67 lamprey were recorded at the underwater antennas just downstream and upstream from the Washington shore count window (Figure 14). Based on directions at antennas upstream from the count window, 60% (n = 40) of the 67 fish moved upstream and then back downstream past the count window. The remaining 40% (n = 27) moved upstream past the count window and passed the dam. The 40 fish that did not pass directly through the count window area moved downstream 1-20 times per fish (mean = 4 times, median = 3 times). Twenty-four of the 40 fish (60%) moved downstream and exited into the tailrace.

In the Bradford Island ladder, a total of 82 lamprey were recorded at the antennas just downstream and upstream from the count window (Figure 14). Based on antennas upstream from the count window, 62% (n = 51) of the 82 fish moved upstream and then back downstream past the count window. The remaining 38% (n = 31) moved upstream past the count window and passed the dam. The 51 fish that did not pass directly through the count window area moved downstream 1-226 times per fish (mean =11 times, median = 2 times). Seventeen of the 51 fish (33%) moved downstream and exited into the tailrace. In both ladders, most of the lamprey (83%) that turned around upstream from the count window did so after being recorded only at the first or second antenna upstream from the count window.

Most upstream point reached by fish that did not pass – The majority of the fish released downstream of Bonneville Dam (n = 442 of 595, 74%) did not pass the dam. The most upstream site recorded for these fish included 151 (34%) in the tailrace, 121 (27%) outside a fishway entrance, 58 (13%) in a collection channel, 31 (7%) inside a transition pool, and 75 (17%) inside a ladder. Six fish (1%) had only records at time of tagging.

Those that turned around in transition pools included 29 fish in the north fishway at PH2, 1 fish in the Bradford Island A Branch and 1 fish in the Cascade Island fishway. Those that turned around in the fish ladder included 21 fish in the overflow section of the Bradford Island B-Branch, 7 fish in the overflow section of the Bradford Island A-Branch, 2 fish in the overflow section of Bradford Island ladder after the junction pool, 2 fish in the overflow section of the Washington-shore fishway, 2 fish in the overflow section of the Cascade Island fishway, 27 fish in the serpentine weir sections at the top of the Washington-shore fishway, 12 fish in the serpentine weir sections just upstream of the Bradford Island count window, and 2 fish in the makeup water channel in the Bradford Island fishway.

Passage times – Median passage times from the first tailrace record to first approach at a fishway and first fishway entry was 1.5 d and 3.6 d, respectively (Table 10). Most lamprey passed quickly into a fishway after their first recorded approach (*median* = 1.5 h), from first fishway entry into a transition pool (*median* = 0.2 h), and through transition pools (*median* = 0.7 h). Passage times were much higher for the segment between first fishway entrance and exit from the top of a ladder (*median* = 75.7 h) and from exiting the transition pool to exiting the fishway into the forebay (*median* = 22.7 h).

Table 10. Summary of radio-tagged adult lamprey passage times at Bonneville Dam in 2008.

Passage segment			Passage times		
Start	Finish	n	Median (h)	Mean (h)	Range (h-d)
Tailrace	Fishway approach	378	36.8	116.8	0.9 h-109 d
Tailrace	Fishway entrance	191	85.3	216.9	1.6 h-129 d
Tailrace	Past dam	138	133.1	228.8	16.9 h-67 d

Fishway approach	Fishway entrance	200	1.5	91.9	0.1 h-105 d
Fishway entrance	Transition pool entry	160	0.2	42.8	0.01 h-50 d
Fishway entrance	Past dam	123	75.4	180.7	8.7 h-64 d
Transition pool entry	Transition pool exit	126	0.7	34.6	0.1 h-61 d
Transition pool exit	Past dam	134	22.7	31.5	3.3 h-6 d

Lamprey passage times in the upper portion of both ladders were calculated between adjacent pairs of underwater antennas. In the Washington-shore ladder, most lamprey passed relatively quickly through the upper ladder, though a few had passage times > 12 h in almost every section (Figure 16). Passage times between the two antennas bracketing the count window ranged from several minutes to 15.2 h (*median* = 0.07 h). Three fish (6%) took more than 12 h to pass this area, and two of these were first recorded at the lower antenna between 0500–0800 h, suggesting a possible daylight effect. Passage times through the serpentine weir section were the longest, on average, of all sections. Times in this portion of the fishway ranged from 0.6 h to more than 7 d (*median* = 1.66 h) (note: this includes time some fish spent moving downstream out of the serpentine section). Total passage times from the junction of the UMT channel to exit the fishway into the forebay ranged from 1.4 h to 8.5 d (*median* = 15.76 h).

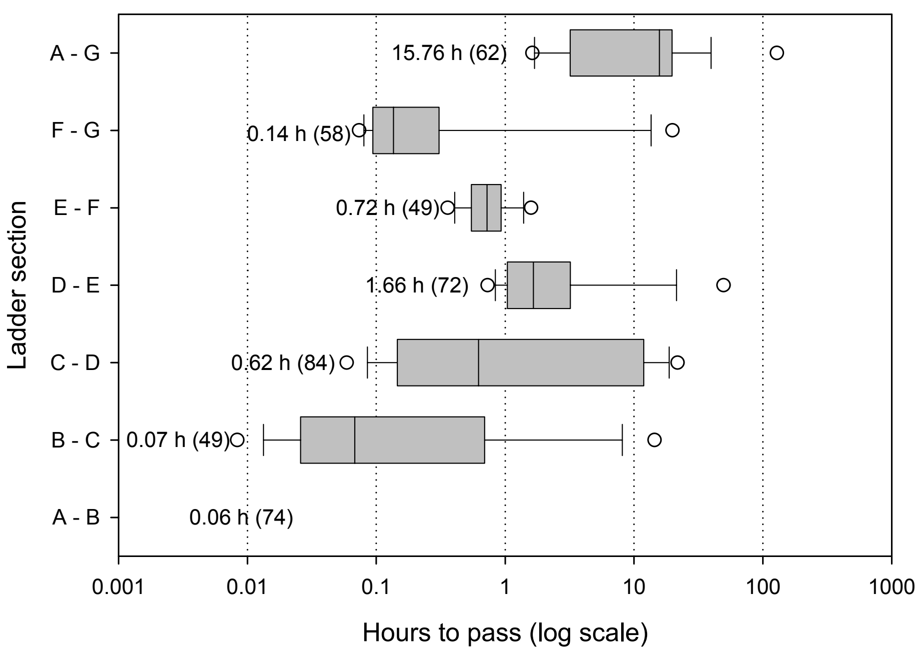

Figure 16. Log-transformed distributions of adult lamprey passage times (h) through the upper Washington-shore ladder at Bonneville Dam. Ladder sections were defined by antenna locations. A = upstream from UMT channel; B = downstream from counting window; C = upstream from counting window; D and E = in serpentine weirs; F = top of serpentine weirs; G =

ladder exit. Box plots show median, quartile, 10th, 90th, 5th, and 95th percentiles. Numbers represent median times (*n*).

Lamprey passage times through the top of the Bradford Island ladder were generally more rapid than through the upper Washington-shore ladder (Figure 17). However, median times for those fish that did not use the LPS structure were 16.8 h from the antenna upstream from the A- and B-Branch junction pool to exit from the top of the ladder, and were similar to the WA shore times. The median time between the pair of antennas that bracketed the count window was 0.05 h and > 90% of the fish passed the window in < 1 h. Lamprey passage times through the serpentine weir section were comparable to those in the Washington-shore serpentine section (Figures 11 and 12).

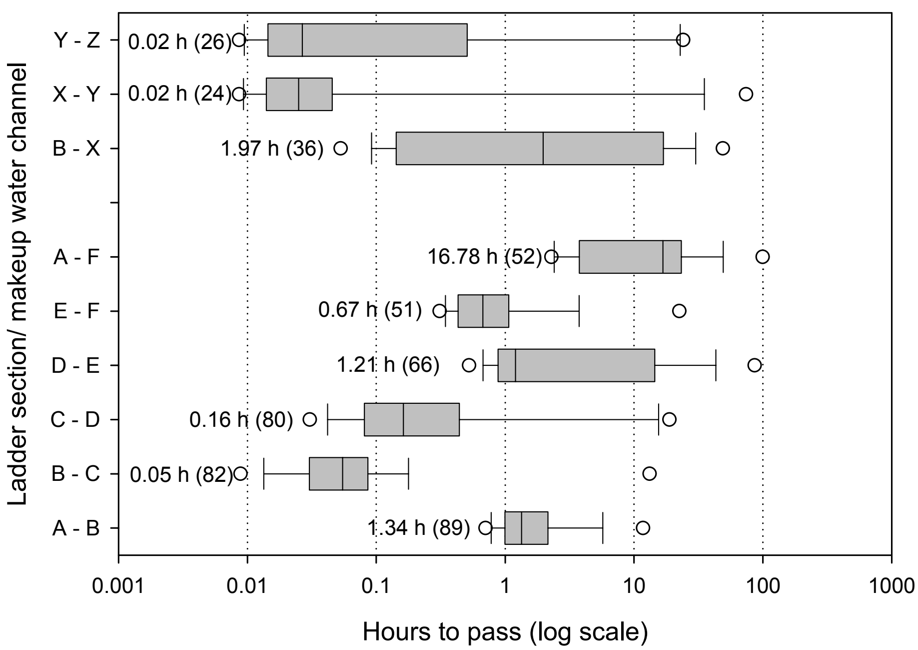

Figure 17. Log-transformed distributions of adult lamprey passage times (h) through the upper Bradford Island ladder at Bonneville Dam. Ladder sections were defined by antenna locations. A = upstream from junction pool; B = downstream from counting window; C = upstream from counting window; D and E = in serpentine weirs; F = ladder exit; X, Y, and Z = in the makeup water channel (MWC). Box plots show median, quartile, 10th, 90th, 5th, and 95th percentiles. Numbers represent median times (*n*).

The Dalles fallbacks

Sixty-one lamprey passed The Dalles Dam, and seven (11%) of these were recorded falling back downstream past the dam. Fallback percentages were 10% (5/48) for fish that passed via the south-shore ladder (East fishway) and 15% (2/13) for those that passed via the north-shore ladder. The median number of days between exiting a fishway and detection downstream from the dam was 14.4 d (*range* = <1 h to 26.0 d). Two of the seven fallback fish reascended a ladder at The Dalles Dam and were last recorded at John Day Dam. Of the fish that did not reascend, two were recorded in the Deschutes River and one was recorded passing John Day Dam prior to falling back at The Dalles a second time.

The Dalles fishway use

Passage efficiency – Ninety lamprey were recording approaching fishways at The Dalles Dam and 61 passed the dam for an overall passage efficiency of 68%. Estimated passage efficiencies through segments of the fishways were within the range calculated at The Dalles Dam in the earlier (1998–2002) telemetry studies, except that efficiency was lower (57%) through the north shore transition pool than in previous years (62–86%; Table 11). Passage efficiencies were 72–82% through the fishway entrance areas, 83–100% through the collection channels, 57–92% through transition pools, and 100% through the ladders (Table 11).

Table 11. The number of unique radio-tagged lamprey that passed through each area within each fishway at The Dalles Dam in 1997-1998, 2000-2002 (as reported in Moser et al. 2005), 2007 (reported in Johnson et al. 2009) and in 2008. Passage efficiency (number of lamprey that passed through the area/number that approached × 100) is in parenthesis.

				Year			
Area	1997	1998	2000	2001	2002	2007	**2008**
				East Fishway			
Entrance	41 (85%)	22 (73%)	52 (87%)	71 (89%)	46 (78%)	18 (83%)	**78 (82%)**
Collection	34 (83%)	21 (95%)	47 (90%)	67 (94%)	43 (93%)	20 (100%)	**64 (83%)**
Transition	27 (79%)	12 (57%)	41 (87%)	52 (78%)	29 (67%)	17 (76%)	**53 (92%)**
Ladder	24 (89%)	12 (100%)	37 (97%)	48 (96%)	28(100%)	[1]13(100%)	**[1]49 (100%)**
Count station	24(100%)	12 (100%)	37 (97%)	48 (96%)	28(100%)	n/a	**n/a**
				North Fishway			
Entrance	18 (67%)	15 (94%)	44 (94%)	34 (77%)	32(100%)	15 (75%)	**32 (72%)**
Collection	14 (78%)	15 (100%)	42 (95%)	34 (100%)	32(100%)	13 (100%)	**23 (100%)**
Transition	11 (79%)	13 (87%)	36 (86%)	24 (71%)	25 (78%)	13 (62%)	**23 (57%)**
Ladder	11(100%)	12 (92%)	33 (92%)	22 (92%)	18 (72%)	[1]8 (100%)	**[1]13 (100%)**
Count station	11(100%)	12 (100%)	33 (100%)	22 (100%)	18(100%)	n/a	**n/a**

[1] Because the count stations were not monitored in 2007-2008, the ladder estimate was calculated from the last transition pool record to the top-of-ladder exit.

Entrance efficiency was highest at the east entrance (79%, n = 58 fish recorded approaching). Efficiencies were 57% (n = 28) at the south spillway entrance, 72% (n = 32) at the north-shore entrance, and 42% (n = 33) at the west Powerhouse entrance.

Passage times –A total of 93 lamprey were detected at antennas at The Dalles Dam or in The Dalles tailrace. Detection efficiency at the tailrace antennas was relatively low, with 28% (n = 26) of the tagged fish recorded at the tailrace sites on their first apparent approach to the dam; 3 of the 23 (13%) were not recorded upstream from the tailrace.

Median passage times from the first tailrace record to first approach at a fishway, first fishway entry, and to pass The Dalles Dam were 5.9, 3.8, and 70.6 h, respectively (Table 12). Most lamprey passed quickly into a fishway after their first recorded approach (*median* = 0.5 h, *n* = 77), from first fishway entry into a transition pool (*median* = 0.0 h, *n* = 75), and through transition pools (*median* = 0.7 h, *n* = 42). In contrast, passage time variability was much higher for the segment between first fishway entrance and exit from the top of a ladder (*median* = 28.8 h, *n* = 61) in part due to time spent exiting and re-entering the fishways. Median fishway entry to top-of-ladder times were 89.5 h (*n* = 20) for fish that exited a fishway into the tailrace versus 23.3 h (*n* = 41) for fish that did not exit.

Table 12. Summary of radio-tagged adult lamprey passage times at The Dalles Dam in 2008.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Min	Max
Tailrace	Fishway approach	23	5.9	18.6	1.1	4.9 d
Tailrace	Fishway entrance	18	3.8	20.1	2.0	5.0 d
Tailrace	Past dam	14	70.6	76.7	1.3 d	6.9 d
Fishway approach	Fishway entrance	77	0.5	10.2	0.0	5.1 d
Fishway approach	Past dam	115	77.7	176.1	8.7	64.2 d
Fishway entrance	Transition pool entry	75	0.01	5.3	0.0	4.1 d
Fishway entrance	Past dam	87	75.4	142.9	9.3	62.3 d
Transition pool entry	Transition pool exit	42	0.7	21.4	0.1	10.7 d
Transition pool exit	Past dam	42	22.6	100.8	4.3	82.5 d

Entrance use – At least 90 lamprey approached fishway entrances in 2008, 77 entered fishways, and 36 subsequently exited back into the tailrace one or more times. The highest percentage of the tagged fish were first recorded approaching the east entrance (*n* = 30, 33%), followed by the north-shore entrance (*n* = 27, 30%), west Powerhouse entrance (*n* = 19, 21%), and south spillway entrance (*n* = 14, 16%). Patterns for first recorded fishway entries were similar: 35 (45%) at the east entrance, 21 (27%) at the north-shore entrance, 11 (14%) at the west Powerhouse entrance, and 10 (13%) at the south spillway entrance.

Distributions of total fishway approaches and entries were generally consistent with first approaches and entries, with the highest percentage of total approaches (48%) and total entries (44%) at the east entrance. Lamprey approached fishways a median of 2 times (*mean* = 3.7 times) per fish. Lamprey entered fishways a median of 1 time (*mean* = 1.6 times) per fish. Those that exited back into the tailrace did so a median of 1 time (*mean* = 1.7 times). The south spillway entrance was exited most frequently (*n* = 19 times), followed by the east entrance (*n* = 17 times) and the north entrance (*n* = 15 times); the west Powerhouse entrances was exited 10 times.

Most upstream point reached by fish that did not pass – Thirty-two fish recorded in the tailrace or at fishways at The Dalles Dam did not pass over the dam. The most upstream site recorded for these fish included 13 (41%) outside a fishway entrance, 10 (31%) inside a transition pool, 4 (13%) at the uppermost antenna monitoring the transition pool (overflow conditions for the entire migration), 3 (9%) in the tailrace, and 2 (6%) in the east fishway collection channel. The 10 that turned around in transition pools included 6 fish in the north fishway and 4 in the east fishway.

John Day summary

Only tailrace and top-of-ladder antennas were deployed at John Day Dam, precluding calculation of most of the passage efficiency and passage time metrics. Thirty-six fish were recorded at either top-of-ladder or tailrace antennas; of these, 24 were recorded at the tailrace site, 21 were recorded at the ladders, and 9 were recorded at both tailrace and ladder sites. Seventeen fish (81%) passed the dam via the south-shore ladder and four (19%) passed via the north-shore ladder. Total dam passage efficiency was 58.3% (21 passed / 36 detected).

Seven of the 21 (33%) lamprey that passed John Day Dam subsequently fell back downstream. Two of the seven reascended John Day ladders; one of these eventually passed McNary Dam, while the other fell back at John Day Dam a second time and was last recorded in the tailrace.

Nine lamprey were recorded at both tailrace and top-of-ladder sites. The median dam passage time for this group was 2.8 d h (*mean* = 4.6 d, *range* =0.3–13.8 d).

McNary summary

Five fish were recorded at telemetry antennas at McNary Dam and four were recorded at fishway sites. All four first approached the dam at the south-shore fishway entrance, passed through the south-shore transition pool, and exited from the top of the south-shore ladder. Median passage times for these fish were 20.7 h from fishway approach to fishway entry, 0.1 h from fishway entry to transition pool entry, 0.2 h from transition pool entry to exit, and 35.0 h from transition pool exit to top-of-ladder exit. None of the four fish were recorded falling back at McNary Dam.

Discussion

Bonneville entrance velocity

Based on entrance efficiencies and net number of entries, running the fishway units in standby mode negatively affected lamprey entry into PH2 fishway entrances. Entrance efficiencies for tagged lamprey (all fish pooled during the treatments) increased from 2% during standby to 9% during normal operation at PH2 north and from 12% during standby to 30% during normal operations at PH2 south. Nighttime entrance efficiencies at PH2 south in 2008 were similar to 2007 (32%) and remained low at PH2 north (< 10%). During standby operation the percentage of total approaches at PH2 entrances was similar to or exceeded the percentage during normal operation but fewer fish entered indicating either: (1) lamprey attached to the face of the dam in the vicinity of underwater entrance antennas for prolonged periods of time or (2) fish swam by entrance antennas searching for fishway entrances and did not enter as a result of low attraction flow or confusing currents.

Additionally we observed more fish exiting PH2 entrances than fish entering during standby operations. In comparison, when water velocities at PH2 fishways was reduced to 0.5 ft head in 2007 we observed improved entrance efficiencies 26% compared to 2% during normal velocity (PH2 north) and 32% compared to 24% (PH2 south) (Johnson et al. 2009). This indicated that reducing the velocities at night improved lamprey passage, especially at PH2 north fishway entrances. The combined 2007 and 2008 results suggest that some reduction in entrance velocity is beneficial for lamprey passage, but that these benefits are variable and that zero attraction flow is probably a deterrent. Entrances with higher velocities (capable of a larger net reduction in velocity) may provide relatively more benefit from velocity reductions than entrances with lower velocities.

The experimental entrance efficiency results in 2008 (as in 2007) were lower than efficiencies calculated in previous non-experimental studies as a result of: (1) discarding fish that approached and entered a fishway during opposite treatments, (2) including all approach attempts, and (3) calculating efficiencies during nighttime hours to make treatment and nontreatment comparisons equal because entrance velocities were manipulated after dark. Caution should be used when comparing the 2008 entrance efficiencies to entrance efficiencies estimated in previous non-experimental studies (i.e. 1997-2002).

Return to Bonneville Dam

The percentage of radio-tagged fish that returned to Bonneville Dam in 2008 (74%) was comparable to results in 2007 (68%) but lower than in previous study years. The cause is unknown, although tag effects are possible. Unlike in the 1997-2002 study years, we were unable to select for larger fish on a day-to-day basis in 2007 and 2008 to minimize tag effects, and therefore transmitters made up a greater proportion of total fish weight and volume. In 2002, the same transmitter (NT6-2) was used on lamprey having a minimum girth of 11.5 cm and the girth percent ranged from 21.0 to 24.9%. In 2007, the mean percent girth was 25.8% and ranged from 21.1–31.4% and in 2008 the mean percent girth was 23.1% and ranged from 19.3-27.9%. Comparison of the return rates for fish greater than 11.5 cm girth for 2007 and 2008 produced estimates higher than for the total sample in both years. In 2007, 75% all fish 11.5 girth or better returned to BO fishway entrance antennas , versus 68% for the full sample. In 2008, 77.6% of all fish 11.5 girth or better returned to BO fishway entrance antennas versus 74% for the full sample). While the estimates for the subsamples are more directly comparable to previous years, we note that differences in tag type and antenna arrays preclude full direct comparison of the 2007-8 subsample rates to previous years.

For teleost fishes, the effects of surgically implanting transmitters have been well studied and have generally confirmed that tags less than 2% of the fishes' body weight do not significantly affect fish behavior, buoyancy, or swimming performance (Jepsen et al. 2002). However, for anguilliform-shaped fish like lamprey which have a narrow body cavity, the diameter of the radio transmitter may be a more limiting factor (Moser et al. 2007). Moser et al. (2005) found that lamprey passage success at Bonneville Dam and passage times from release sites to the dam was negatively correlated with percent weight and percent girth of the radio tag relative to the fish (i.e. lamprey bearing large transmitter by volume required significantly more time to approach the dam and were less successful at passing the dam). Notably, results from our logistic regression analysis revealed no significant association between the tag girth to fish girth ratio and the probability of successful return to Bonneville Dam after accounting for other variables.

Fish that were not detected at Bonneville Dam could have had transmitters that were shed, may have abandoned upstream migration, may have been consumed by predators, may have died from tagging effects or could have avoided detections at fishway entrance antennas which are positioned shallow in the water column (K. Tolotti, University of Idaho, personal communication). Transmitter failure was relatively unlikely since the average life span of transmitter that were turned on and monitored throughout the season averaged between 123-145 d. In addition, results from the 2008 sub-sample of double-tagged (radio and HD PIT tag) fish indicated high detection efficiencies for the telemetered fish (Keefer et al. *in review*).

Results from our logistic regression analysis revealed no significant association between fish weight, percent fat, transmitter girth to fish girth ratio, presence of a HD PIT tag, release site, person performing the surgery, or location where fish was trapped and the probability of successful return to Bonneville Dam in 2008. We did detect a significant fish length effect where longer fish were more likely to return to Bonneville Dam. In a similar evaluation that used both radio-tagged and HDX-PIT tagged fish identified size and tag type as significant predictors of passage at Bonneville Dam (see Keefer et al. 2009). Further, in several years of HDX-PIT tag studies with Pacific lamprey, we found that larger fish were far more likely to pass upstream past Bonneville Dam and dams further upstream than were smaller fish (Daigle et al. 2008; Keefer et al. *in press*). Lastly, Moser et al. (2007) found that lamprey bearing larger transmitters (by volume) took longer to return to Bonneville Dam after being released downstream. Longer tailrace residence times would potentially expose fish to increased predation by sea lions (early in the run) and white sturgeon.

In the telemetry data, we did detect a significant tag date effect. Fish that were tagged later in the year were less likely to return to Bonneville Dam. These results contrast with 2007 results where we observed that fish tagged later in the year were more likely to return. These lower returns later in the year may have been associated with warmer water temperatures and increased mortality and predation. We note, however, that water temperatures and river discharge during the 2008 lamprey migration were close to mean values.

Bonneville fishway use and fallback

Fallback percentages at Bonneville Dam were lower in 2008 (17%) than in 2007 (28%) but higher than the ~1% reported in previous years' radiotelemetry studies (Moser et al. 2005). Some of these fallback events were possibly false positives, meaning that detection on an aerial antenna in the tailrace was the result of lamprey located in the forebay or on an LPS structure. However, at least 3 of the 26 reported fallbacks were valid based on detections on underwater antennas in fishways. Further, the extended times between fish exiting the top of a fishway and being detected on a downstream receiver (*median* = 12.7 d) also suggests that many of the detections on aerial antennas in the tailrace were valid fallbacks. The highest percentage of fallbacks was reported for lamprey that exited the Bradford Island fishway. This is consistent with radiotelemetry studies for salmon and steelhead that report significantly higher fallback for fish exiting the Bradford Island fishway than for those exiting the Washington-shore fishway (Reischel and Bjornn 2003; Boggs et al. 2004). Fish that exit the Washington-shore fishway encounter a clearly defined shoreline that orients them upriver. In contrast, some fish that exit the Bradford Island fishway follow the shoreline of Bradford Island into the spillway forebay, and subsequently fall back over the spillway.

Lamprey behavior and passage times near the Bonneville Dam count windows and in the serpentine weir sections suggest that this area continues to cause passage problems. While many fish passed rapidly through upper portions of both the Washington-shore and Bradford Island, some fish experienced delays. In addition, more than half of radio-tagged lamprey that passed upstream of the count windows then moved downstream past the count windows in 2007 and 2008. A higher percentage of the fish at Washington-shore compared to Bradford Island backed all the way down the ladder and exited into the tailrace after moving downstream past the count window. The high passage efficiencies (84-99%) in the count window section do not take into account the upstream and downstream behavior of lamprey around window and serpentine section of the fish ladders. It was not clear whether conditions at the count windows, conditions in the serpentine sections, or a combination of these factors affected behavior in this area. However, we note that many fish were recorded at one or more antennas in the serpentine sections prior to moving downstream past the count windows. Lamprey behaviors and residence times in the upper ladders and near count windows were generally similar to those reported by Moser et al. (2005), including the relatively high turn-around rates in and near the serpentine weir sections. A difference between the 2008 results and earlier studies was that more fish were recorded exiting from the top of the makeup water channels in 2008.

Repeated passes in front of the count stations are consistent with results from the night-time video evaluations (e.g., Clabough et al. 2008). In the video analysis, lamprey were observed moving downstream past windows in both fish ladders and often in numbers greater than the upstream counts in the Washington-shore fish ladder. This behavior is of concern because of the potential bias introduced into lamprey counts and because it reflects passage difficulty in this area.

Full-dam lamprey passage efficiency (approach to top of ladder) at Bonneville Dam was slightly higher in 2008 (32%) than in 2007 (31%) but lower than in previous years. Efficiency estimates through most sections of the fishway at Bonneville Dam were similar to or lower in

2008 than in 2008 with the exception of the PH1 collection channel. Passage efficiencies were lower PH1 and PH2 entrances, PH1 and spillway transition areas, and PH2 ladder section. Passage efficiencies in 2008 compared to the previous years (1997-2002, 2007) were lower at the PH1 entrances, collection channel, and transition pool and at the PH2 and spillway entrances, transition pools, and ladder sections.

Passage times for lamprey at Bonneville Dam (first detection in the tailrace to top-of-ladder) were lower in 2008 (5.5 d) than in 2007 (7.8 d) and within the range of previous years (4.4 d in 2000 to 11.0 d in 2001). Among passage segments, passage times at Bonneville Dam were longest from first fishway approach to exit the top of a ladder (*median* = 3.2 d), likely because of multiple fishway exits and re-entries by some fish. However, this metric was significantly shorter then reported in previous years (from first detection outside an entrance to the last detection at the top-of-ladder exit): 9 d in (2002) and 4-6 d (1997-2001). Passage times for segments within the fishway in 2008 were longest from the time lamprey exited a transition pool to exiting a ladder into the forebay (*median* = 22.7 h), in part because of the milling behavior at the count windows, relatively slow passage through the serpentine weir section of the ladder, and the cessation of movement during daytime.

The Dalles fishway use and fallback

Lamprey passage efficiencies and passage times at The Dalles Dam in 2008 were generally within the ranges recorded in previous studies or were slightly higher. The 11% fallback percentage in 2008 at The Dalles Dam was higher than the 2–4% recorded in earlier telemetry studies (Ocker et al. 2001; Moser et al. 2005) but lower than the 29% recorded in 2007 (Johnson et al. 2009). It is also possible that smaller mean fish size, or some other factors (e.g., fish condition) in 2007-2008 predisposed fish to falling back compared to the 1997-2002 results.

Fishway use behaviors in 2008 were qualitatively similar to those in prior years. Fish principally used the north-shore and east Powerhouse entrances, with relatively few fish recorded at the spillway or west Powerhouse sites. This likely represents the distribution of attraction flow in the tailrace. Relatively higher use of the north-shore entrance in 2008 versus 2007 may reflect the substantially higher spill volume in 2008. As in other years, lamprey passed The Dalles Dam more quickly, on average, than they passed Bonneville Dam. This may reflect size-based selection for larger fish reaching The Dalles Dam (e.g., Keefer et al. *in press*), more favorable passage conditions near fishway entrances or at count windows, or the effects of warming water temperatures or increased fish motivation.

Conclusions and Recommendations

Fewer radio-tagged fish entered fishways during the standby operation at PH2 entrances, presumably because there was less attraction flow. Once fish entered the fishway during the standby operation they were more likely to exit the fishway. During previous studies at

Bonneville Dam, reducing fishway entrance velocity showed promise for aiding adult lamprey entrance and passage. In 2008, however, zero head differential at entrances had an overall negative effect on lamprey passage. Consequently, turning off fish units for debris removal from the trash racks should probably occur during non-peak lamprey passage times. In addition, reducing the total standby time would likely be beneficial to lamprey passage at Bonneville Dam.

In 2007, reduced velocity improved entrance efficiency when compared to normal operations, but the low velocity condition attracted fewer fish to the entrance area (Johnson et al. 2009). We note that more fish remained in the fishway during the low-velocity operation in 2007 and that low velocity was substantially more effective for passing adult lamprey than the zero-head standby operation in 2008. The combined results suggest that an intermediate fishway velocity/head would most efficiently balance attraction and efficiency. Additional experiments that test one or more alternate treatments (i.e., low velocity, intermediate velocity, high velocity, supplementary attraction, etc.) may help identify conditions that maximize lamprey passage.

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